ROLE OF INTERGRANULAR CONTACTS ON MECHANISMS CAUSING LIQUEFACTION & SLOPE FAILURES IN SILTY SANDS

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Annual Project Summary
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Non-technical summary
This research seeks to develop a fundamental understanding of the behavior of silty sands under undrained loading conditions during earthquakes. Particular focus is on stress-strain behavior, collapse potential (liquefaction potential), and post-liquefaction shear strength from a microscopic mechanistic point of view. The goal is to improve our ability to evaluate liquefaction potential, flow-deformation potential, seismic slope stability of earth structures, dams and embankments built of natural silty sands and develop design strategies to mitigate earthquake damage and minimize losses.

Annual Technical Summary Report

This research seeks to develop a fundamental understanding of the behavior of silty sands under undrained loading conditions during earthquakes. Particular focus is on stress-strain behavior, collapse potential (liquefaction potential), and post-liquefaction shear strength from a microscopic mechanistic point of view. The goal is to improve our ability to evaluate liquefaction potential, flow-deformation potential, seismic slope stability of earth structures, dams and embankments built of natural silty sands/sandy silts and develop design strategies to mitigate earthquake damage and minimize losses.

In particular the overall ultimate aim of this research is to:

(a) develop an understanding of the physical nature of inter-fine and inter-granular frictional contacts in <u>silty sands/sandy silts</u> at different void ratio and fines content levels and their effects on liquefaction resistance and post-liquefaction strength,

(b) develop a new unified method to characterize cyclic and post-liq. strength characteristics,

(c) re-evaluate the current methods of assessing liquefaction potential and liquefaction-related damage potential, based on this new understanding, and

(d) develop an improved method for assessment of liquefaction potential and related damage.

The current-two-year-funded period (1999-2000) covers task (a) above.

A. Work Performed

The ongoing work during this reporting period (Jan.1999-Sept. 2000) specifically focused on the following sub tasks.

- Task I: Development of a physically sound conceptual and theoretical framework to understand the *fundamentally different* roles of fines and inter-granular frictional contacts, at different "density levels" and different fines content levels, on the undrained behavior of silty soils, and
- Task II: Experimental evaluation of the above framework using new and other available undrained stress-strain data, refinement of the framework, and development of guidelines for determination of liquefaction resistance and post-liquefaction strength.

A.1 Development of Framework for Analysis: The preliminary hypothesis proposed in the research proposal has been further developed. Based on our prior preliminary research on the nature of soil microstructure, it was *first* realized that silty sand is indeed a soil consisting of “multi-skeleton-structure” with each skeleton having a different compressibility. Its stress-strain behavior is an integrated response of the scale-level dependent response of the different “*skeletons*”. The traditional approach based on critical state soil mechanics concepts alone using void ratio or state parameter as the primary state variables is insufficient to characterize the measured response. This is so because the relative contributions of the different skeletons differ significantly as the silt content and void ratio of silty sand varies. Viz. the mechanisms controlling the stress-strain behavior are derived from contributions by different skeletons, each offering a different degree of contribution, depending on void ratio and fines contents. It also depends on the type of fines (plastic or not). A realistic conceptual model should consider appropriate state variables that describe the nature of active grain contacts within each skeleton and the interaction between the skeletons.

As a first-order approximation, a *gap-graded* silty sand was considered and modeled as a composite dual-level skeleton consisting of *single-sized* finer-grain skeleton and a *single-sized* coarser-grain skeleton (Fig.1, Table 1). With due intuition and semi-theoretical consideration for interactions among the coarser grains, the finer grains, and between them, two sets of state variables, the intergranular (e_c) and interfine (e_f), and the equivalent intergranular [$(e_c)_{eq}$= $[e+(1-b)fc)]/[1-(1-b)fc]$, 0<b<1, fc=fractional silt content by weight=FC/100, Fig.1] and interfine [$(e_f)_{eq}=e/[fc+(1-fc)/(R_d)^m]$, Fig.2, where 0<m<1, and $e_c>e_{max,HC}$] void ratios were introduced as *indices of active grain contact density* for each skeleton and for the global soil, respectively (Thevanayagam 1999). A threshold fines content [FC_{th}] relationship that prescribes when to use each of the above indices to assess the seismic response of silty soils was developed. The formulation was evaluated using experimental data on a gap-graded silty soil.

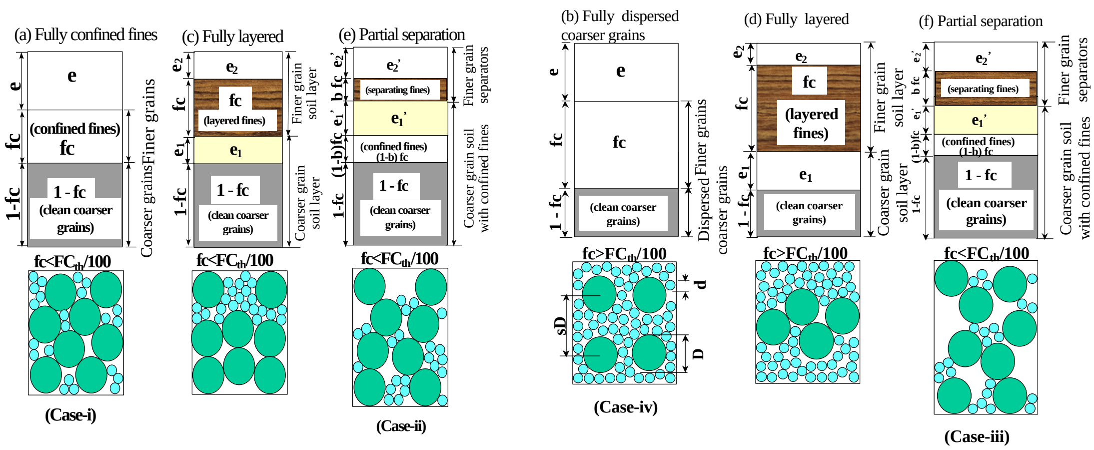
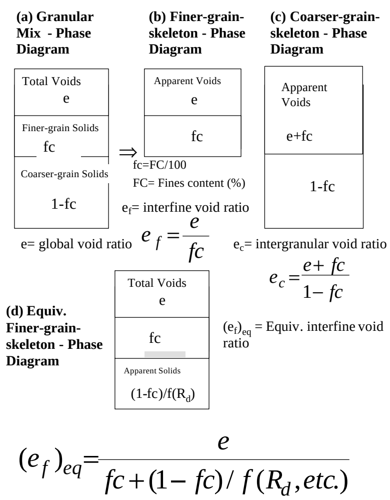


Fig.1 Microstructure and intergranular matrix phase diagram



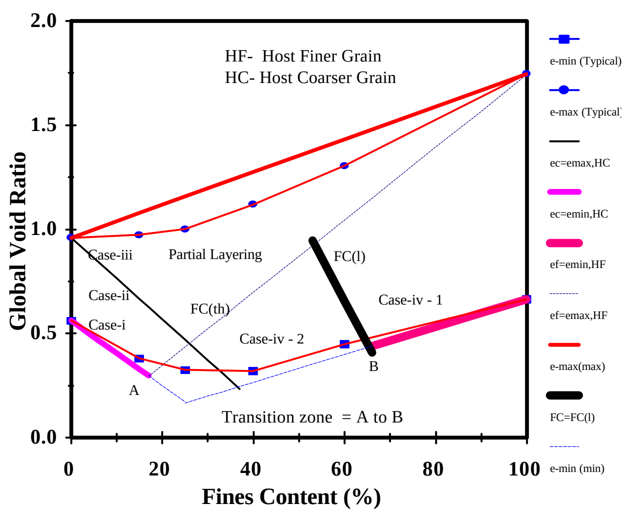


Fig.2 Intergranular contact indices

Fig. 3 Intergranular matrix diagram – Mix Classification

Table 1: Granular Mix Classification (Ref. Figs. 1-3)

Case	FC	e_c	e_f	***Roles of coarser-grains and finer-grains***	Contact Index Void Ratio	Fig.
i		$e_c<e_{max,Hc}$	$e_f>e_{max,HF}$	Finer grains are inactive (or secondary) in the transfer of inter particle forces. They may largely play the role of "filler" of intergranular voids. The mechanical behavior is affected primarily by the coarser grain contacts.	$(e_c)_{eq}$	1a
ii	$FC<FC_{th}$	e_c near $e_{max,Hc}$		Finer grains support the coarser-grain skeleton that is otherwise unstable. They act as a load transfer vehicle between "some" of the coarse-grain particles in the soil-matrix while the remainder of the fines play the role of "filler" of voids.	$(e_c)_{eq}$	1e
iii		$e_c>e_{max,Hc}$		Finer grains play an active role of "separator" between a significant number of coarse-grain contacts and therefore begin to dominate the strength characteristics.	$(e_c)_{eq}$	1f
iv-2	$FC_{th}<FC<FC_l$		$e_f<e_{max,HF}$	The fines carry the contact and shear forces while the coarser grains may act as reinforcing elements embedded within the finer grain matrix.	$(e_f)_{eq}$	1b
iv-1	$FC_l<FC$	$e_c>>e_{max,Hc}$	$e_f<e_{max,HF}$	The fines carry the contact and shear forces while the coarser grains are fully dispersed.	$(e_f)_{eq}$	1b

Notes: $e_{max,Hc}$, $e_{max,HF}$ = maximum void ratio of the host sand (coarser grains) and host fines (finer grains) media, respectively. They are the limiting void ratios beyond which each soil (clean coarser grained soil, pure fine grained soil) has no appreciable strength. FC_{th}=Threshold finer grains content, and FC_l = limiting finer grains content. The magnitudes of FC_{th} and FC_l depend on the size disparity ratio (R_d=D/d) of the size of the coarser (D) and finer (d) grains, shape, packing, $e_{max,Hc}$, and $e_{max,HF}$ as shown elsewhere (Thevanayagam 1998-2000). Intergranular void ratio (e_c) =[$e+fc$]/[$1-fc$], (fc=FC/100, FC=finer grain content by weight). Interfine void ratio (e_f) =e/fc, s=1+a(d/D)=1+a/R_d, where a=10 (approximately).

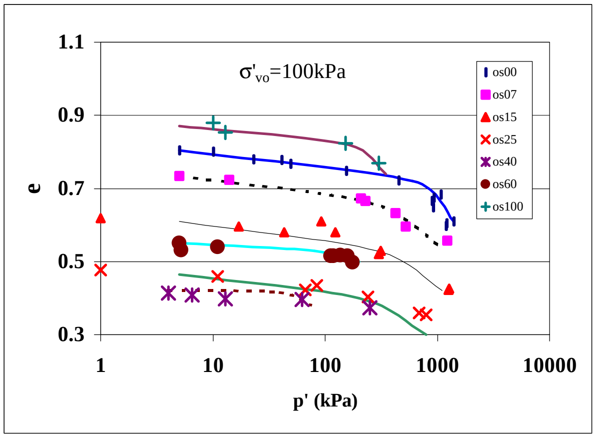
$$FC_{th} \le \frac{100 e_c}{1+e_c+e_{\max,HF}}\% = \frac{100\,e}{e_{\max,HF}}\% \;; \qquad FC_l \ge 100\left[1-\frac{p\,(1+e)}{6\,s^3}\right]\% = 100\left[\frac{\frac{6s^3}{p}-1}{\frac{6\,s^3}{p}+e_f}\right]\% \ge FC_{th};\ e_f \le e_{\max,HF}$$

A.2 Experimental Research and Data Base Development: An experimental program to study the behavior of silty soils was initiated. More than about 100 undrained monotonic and cyclic tests have been conducted to date. In addition, a database of existing data on monotonic and cyclic behavior of silty sands has also been developed. This combined database of new and existing data is continually being updated and analyzed. The analysis of this data is currently underway.

Analysis of the data indicates promising results, as discussed next.

A.3 Analysis and Results: The newly proposed contact density indices correlated well with (a) cyclic strength, (b) post-liquefaction strength, (c) collapse potential, and (d) strain-energy required to trigger liquefaction, etc. Figs.4b, 5b & 6b indicate that gap-graded silty sand [at $FC<FC_{th}$] behaves similar to the host sand when compared at the same $(e_c)_{eq}$. Sandy silt [at $FC>FC_{th}$] behaves similar to the host silt when compared at the same $(e_f)_{eq}$ (Fig.4c&5c). The behavior of each soil mix is different and no unique correlation is found when compared using traditional global void ratio e (Figs.4a, 5a, 6a) (Thevanayagam et al. 1999, 2000a-c). Further work indicates that these new contact indices also correlated well with shear modulus, shear wave velocity, and stress-strain behavior, and post-liq vol. strain of silty soils and sands alike, in a consistent unified manner

(Thevanayagam and Mohan 2000, Thevanayagam 1999). This illustrates that the first-order intergrain contact indices $(e_c)_{eq}$ and $(e_f)_{eq}$ are useful to characterize seismic behavior of gap-graded silty soils and offers further confidence to this research. Further research is ongoing.



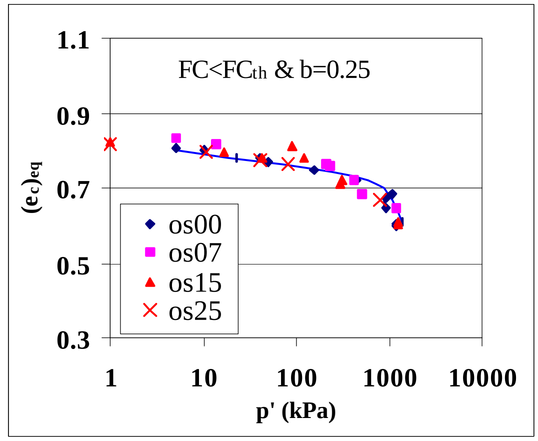
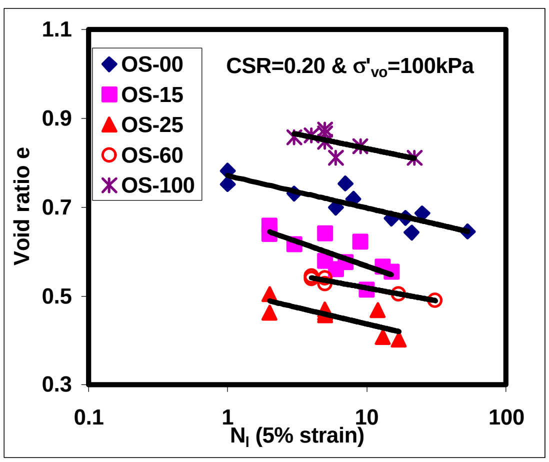


Fig.4a: Steady state data: e vs. p' (FC= 0 to 100%). Fig.4b: Steady state data: $(e_c)_{eq}$ versus p' (FC<FC_{th})

[Notation: p'=(s'$_1$+2s'$_3$)/3; os25= Ottawa sand mixed with 25% silt]



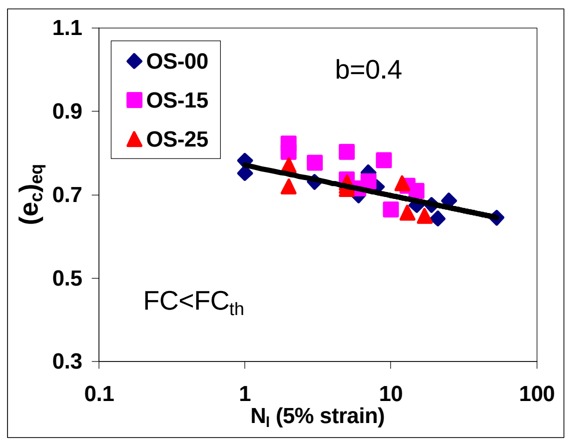
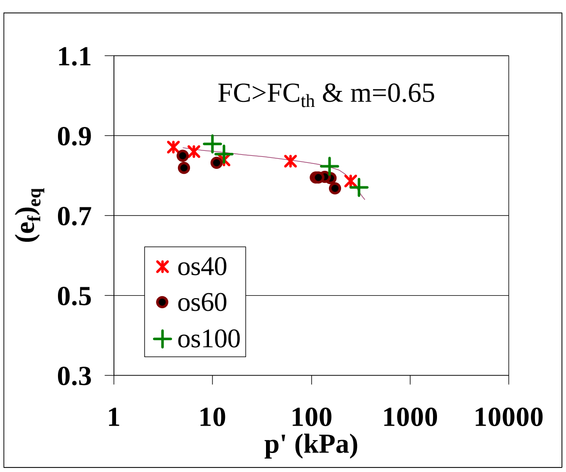


Fig. 5a *e* Vs No. cycles (N_l) to liquefaction (FC= 0 to 100%) Fig.5b $(e_c)_{eq}$ Vs N_l (FC<FC_{th})



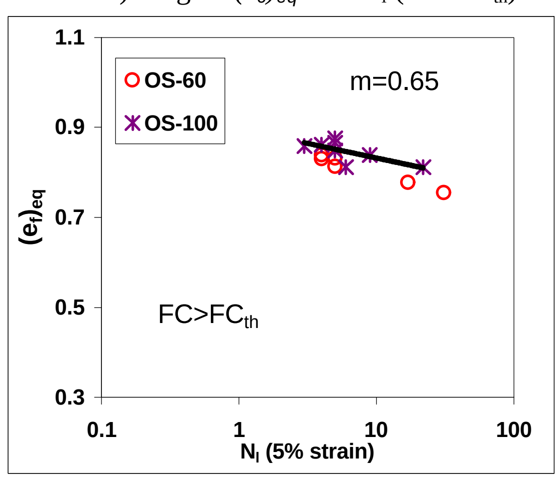


Fig. 4c $(e_f)_{eq}$ *Vs. p'(steady state) (FC>FC_{th})* *Fig. 5c* $(e_f)_{eq}$ *Vs. N_l (FC>FC_{th})*

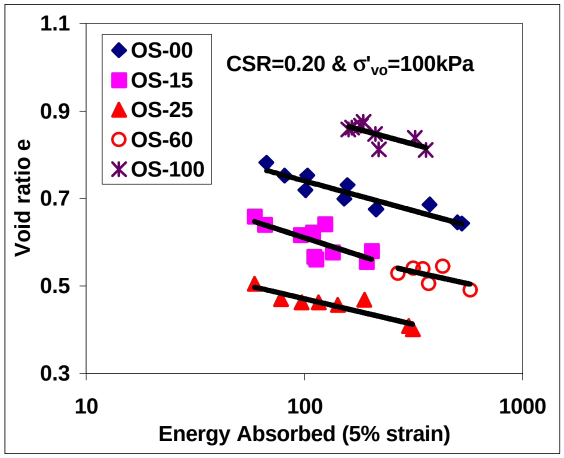


Fig.6a *e* Vs. Strain Energy (kNm/m^3) required to cause liquefaction (FC = 0 to 100%)

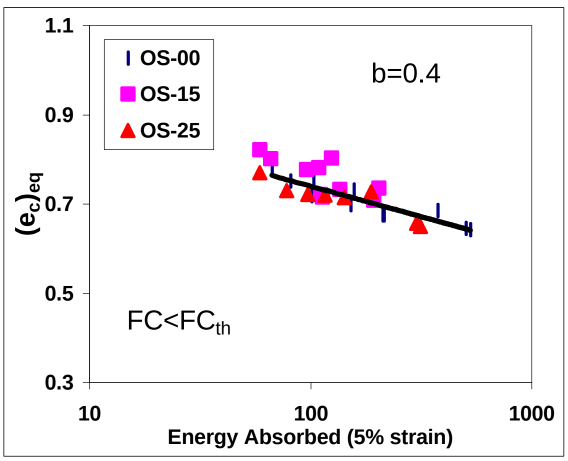


Fig.6b $(e_c)_{eq}$ Vs. Strain Energy (FC<FC$_{th}$)

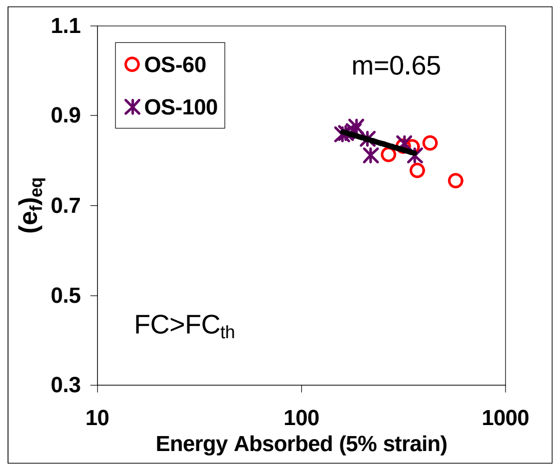


Fig.6c $(e_f)_{eq}$ Vs. Strain Energy (FC>FC$_{th}$)

B. Research Highlights – Breakthrough

Significant new understanding of the behavior of silty soils was developed during this research. A few highlights of the results to date are summarized in some detail in the following.

B.1 Steady State vs. e, $(e_c)_{eq}$ and $(e_f)_{eq}$ Relations: Fig.4a shows the steady state data obtained from triaxial compression tests on sand-silt mixes at different silt contents (00, 07, 15, 25, 40, 60, and 100%), plotted in void ratio e versus mean effective stress at steady state [$p' = (s'_1+2s'_3)/3$] plane. At the same void ratio, the mean stress at steady state decreases with increase in silt content up to about 25% as would be predicted according to the hypothesis proposed (Fig.1, Table 1). Beyond about 25% silt content the trend reverses as hypothesized.

Fig.4b shows the data up to 25% silt content (FC<FC$_{th}$) plotted against the new equivalent intergrain contact index void ratio $(e_c)_{eq}$, semi-theoretically developed during this research. The data fall in a narrow band, surrounding the data for the host sand, supporting the proposed hypothesis (Table 1, Fig.1) and indicating potential success of this research. Similar agreement

was found when the data for 40, 60, 100% silt content ($FC>FC_{th}$) were plotted against $(e_f)_{eq}$ (Fig.4c).

***B.2 Cyclic strength vs. e, $(e_c)_{eq}$ and $(e_f)_{eq}$ Relations*:** Fig.5a shows the number of cycles required to cause liquefaction at a constant cyclic stress ratio (CSR=0.2, σ'_{vo}=100kPa) versus void ratio. Similar trend as observed in steady state (Fig.4a) is observed. But when compared against $(e_c)_{eq}$ in Fig.5b, all data for $FC<FC_{th}$ fall in a narrow band as is the case for steady state (Fig.4b). Similarly, the data for sandy silt ($FC>FC_{th}$) correlates well with $(e_f)_{eq}$ (Fig.5c).

***B.3 Strain Energy required to cause liquefaction vs. e, $(e_c)_{eq}$ and $(e_f)_{eq}$ Relations*:** Fig.6a shows the strain energy required to cause liquefaction at a constant cyclic stress ratio (CSR=0.2, σ'_{vo}=100kPa) versus void ratio. Similar trend as observed in cyclic strength and steady state (Fig.4a&5a) is observed. But when compared against $(e_c)_{eq}$ in Fig.6b, all data for silty sand ($FC<FC_{th}$) fall in a narrow band as is the case for cyclic strength and steady state (Fig.4b&5b). The data for sandy silt ($FC>FC_{th}$) correlates well with $(e_f)_{eq}$ (Fig.6c).

The above findings are significant breakthroughs. It indicates the existence of a contact index, simple enough, to characterize the behavior of silty soils in a unified manner. The new index consistently correlates well with the various strength characteristics (steady state, collapse potential, cyclic strength, strain energy, shear wave velocity, post-liq vol. strain, etc.). This is an indication that it is possible to explain the behavior of silty soils in a consistent and fundamental way and develop rational methods for liquefaction potential assessment and related damage potential.

C. Outlook

C.1 Success: Based on the results so far, it is expected that this research will produce new understanding of the behavior of silty soils during earthquakes and lead to development of rational methods for mitigation design.

***C.2 Current Limitations*:** While the above findings are promising, at the present time, the main limitation is due to the gap-graded nature of the soils experimented with, and the theoretical development that pertains to gap-graded two-size particulate system. The number of soils experimented with is also limited. Further research is needed to go beyond these limitations and develop a general understanding of the behavior that pertains to all silty soils, and treat all non-plastic silty soils and sands alike under a single formulation.

C3. Further Research: Further research addressing the above issues is ongoing.

D. Reports and Papers

D.1 Development of Framework for Analysis: A report entitled "*Relative roles of coarser and finer grains on undrained behavior of granular mixes*" that summarizes this has been prepared. A technical paper on the same title has been submitted for publication, ASCE J. Geotech. Eng. The abstract of this is presented below.

- *ABSTRACT:* The stress-strain behavior of granular mixes containing coarser and finer grains is derived from a combination of inter-coarser grain and interfiner grain contacts and interactions thereof. Simple analysis of a two-sized particle system with large size disparity is presented to highlight when coarser or finer grain contacts become dominant. The intergranular (e_c), interfine (e_f), and a set of newly introduced equivalent intergranular [$(e_c)_{eq}$], interfine $(e_f)_{eq}$ contact index void ratios are identified as primary indices of intergrain contact density (per grain). Global void ratio is identified as the secondary index. Depending on e_s, e_f, and $(e_f)_{eq}$, the mechanical behavior of a granular mix can be categorized into five subgroups. Each index is dominant for a certain group. The threshold finer grain contents and threshold intergranular void ratios delineating the transition boundaries between these subgroups are presented. Using these indices, the behavior of the mix in each group is qualitatively further characterized in terms of the behavior of either the host coarser grain or the finer grain medium. Exceptions are also identified. Trends in undrained monotonic and cyclic stress-strain and strength behavior of the mix relative to the host coarser or finer grain medium are presented for each group. This is experimentally evaluated for gap-graded silty soils. Detailed evaluation is presented elsewhere. The results provide a mechanistic understanding of possible microscopic mechanisms that affect the liquefaction and post-liquefaction response of man made and natural deposits of silty and gravely sands. It can also be used to develop guidelines for liquefaction mitigation design. *Judicious caution is called for when this is extrapolated to well graded or layered soils.*

D.2 Experimentation and Analysis: A database of existing data on monotonic and cyclic behavior of silty sands has been developed. It is continually being updated and analyzed. In addition, an experimental program was also developed and monotonic and cyclic triaxial tests were conducted on a host sand mixed with *non-plastic* silt in different proportions. This data and other available data were analyzed in light of the hypothesis presented in Fig.1 and Table 1. The findings are presented in a series of papers. A few abstracts as follows.

- "*Liquefaction potential and undrained fragility of silty sands*", 12th *World Conf. on Earthq. Eng., New Zealand, 2000*: *ABSTRACT* - Observations from recent earthquake case histories indicate that natural and man made fills containing a mix sands, silt, and/or gravel do liquefy and cause lateral spreads, defying conventional wisdom. The knowledge gained from past three decades of research on clean sands does not directly translate to such soils. Whether the presence of silt adversely or beneficially affects liquefaction and the collapse potential of silty soils is a contentious issue. The mechanisms leading to liquefaction and large deformation in such soils are more complex. This requires a greater understanding of the soil microstructure and the contributions of soil particles of different sizes to its mechanical response. A framework for analysis of the undrained stress-strain behavior, shear strength and collapse potential of granular mixes ranging from clean sands to pure silts (or gravel) in terms of intergranular and interfine friction is presented. The primary mechanisms affecting the mechanical response of silty (or gravely) soils are identified. New intergrain contact indices are presented to evaluate the liquefaction potential and large undrained deformation characteristics at various silt/gravel contents. This is followed by experimental evaluation of the framework. *The behavior of such granular mixes deserves a greater further detailed study before they can be reliably applied to natural soils*.

- *"Contact Index and Liquefaction Potential of Silty and Gravely Soils": 14th ASCE Engineering Mechanics Conference, Austin, Texas, May 2000:* Abstract -- A framework for analysis of liquefaction potential of granular mixes ranging from clean sands to pure silts (or gravel) with due consideration for intergranular and interfine friction within a granular mix is presented. New intergrain contact density indices $(e_c)_{eq}$ and $(e_f)_{eq}$ are presented to evaluate their liquefaction potential. The usefulness of these indices is evaluated using stress controlled undrained cyclic triaxial tests conducted on specimens prepared by mixing a silt and clean sand in different proportions. The new indices correlate well with cyclic strength and strain-energy required to trigger liquefaction.

- *"Effect of Non-Plastic Fines on Undrained Cyclic Strength of Silty Sands": ASCE Conf. GeoDenver 2000. Abstract* - Whether the presence of silt adversely or beneficially affects liquefaction and the collapse potential of silty soils and how to evaluate cyclic strength behavior of a sand containing different silt contents are contentious issues. The purpose of this work is to investigate this question. Stress controlled undrained cyclic triaxial tests were conducted on specimen prepared by mixing a sand with silt in different proportions. The cyclic stress ratio (CSR=0.2) and confining pressure (100 kPa) were maintained constant. Relationship between no. of cycles required to cause liquefaction (at 5% axial strain) versus void ratio, and newly introduced equivalent void ratio indices based on intergrain contact density considerations are presented. Cyclic strength correlates well with the latter indices.

- *"Liquefaction in Silty Soils – Considerations for Screening and Retrofit Strategies", 2nd International Workshop on Mitigation of Seismic Effects on Transportation Structures Sept.13-15, 2000, Taipei, Taiwan: Abstract* - Current techniques for liquefaction screening, ground modification for liquefaction mitigation, and post-improvement verification rely on knowledge gained from extensive research on *clean sands*, field observations of liquefied ground, and judicial correlation of normalized penetration resistance [$(N_1)_{60}$, q_{c1N}] or shear wave velocity (v_{s1}) data with field liquefaction observations. Uncertainties prevail on the direct extrapolation of such techniques for silty soil sites. Many silty soil sites in Kobe, Turkey, and Taiwan did liquefy. They offer a test bed opportunity to study these questions. This paper examines laboratory data on liquefaction resistance, strength, and v_{s1} of sands and silty soils using grain contact density as the basis. Effect of silt content on cyclic resistance, strength, $(N_1)_{60}$, q_{c1N}, v_{s1}, m_v, and c_v is examined in this light. Rational insights for extrapolation of the current screening techniques to silty soils are offered. Thoughts on modifications necessary to the traditional densification, drainage, and permeation grouting techniques to make them viable for silty soils are offered.

D.3 References and Reports

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